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THE INTERPRETATION OF HARD X-RAY POLARIZATION
MEASUREMENTS IN SOLAR FLARES

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ABSTRACT

We review recent observations of polarization of moderately hard X-rays in solar flares and compare them with the predictions of recent detailed modeling of hard X-ray bremsstrahlung production by non-thermal electrons. We find that the recent advances in the complexity of the modeling lead to substantially lower predicted polarizations than in earlier models and more fully highlight how various parameters play a role in determining the polarization of the radiation field. The new predicted polarizations are comparable to those predicted by thermal modeling of solar flare hard X-ray production, and both are in agreement with the observations. In the light of these results, we propose new polarization observations with current generation instruments which could be used to discriminate between non-thermal and thermal models of hard X-ray production in solar flares.

Subject Headings Sun: flares - Sun: X-rays - X-rays: bursts.

I. INTRODUCTION

Tramiel, Chanan and Novick (1984), or TCN for short, have recently reported observations of polarization in moderately hard (5-20 keV) X-rays occurring in solar flares. In contrast with earlier observations (Tindo et al. 1970, 1972a, 1972b; Tindo, Mandel'stam and Shuryghin 1973; Nakada, Neupert and Thomas 1974; Tindo, Shuryghin and Steffen 1976), these new measurements exhibit low degrees of polarization ($\lesssim 5\%$). In this article we comment on the significance of these new measurements for models of hard X-ray production in solar flares, in particular, on the issue of whether impulsive, solar flare hard X-ray emission is predominantly a thermal (e.g. Crannell et al. 1978; Brown, Melrose and Spicer 1979; Smith and Lilliequist 1979) or non-thermal (Lin and Hudson 1971; Brown 1971; Petrosian 1973; Kane 1974) process. Low polarizations are generally considered to be indicative of a near isotropy of the distribution of bremsstrahlung-producing electrons, a situation hitherto thought to arise more naturally in thermal models. Here we shall discuss the significance of such low hard X-ray polarization measurements of non-thermal models. We shall show that such a low polarization result can occur in non-thermal models, and we shall discuss the ways in which the degree of X-ray polarization is correlated with the parameters of these models.

The characteristics of the hard X-ray emission from solar flares can give important information about the underlying population of energetic electrons and hence, indirectly, about the mechanisms by which that electron population is created. It has been clearly demonstrated (e.g. Brown 1975) that we cannot discriminate between non-thermal and thermal models on the sole basis of the hard X-ray spectral form. General attention, therefore, has been turned to other characteristics of the hard X-ray emission, such as its spatial structure, directionality and polarization. The large (up to 40%)

polarization observed in the early 1970's (see Somov and Tindo 1978, and references therein) implies a non-isotropic distribution for the electrons and therefore favors a non-thermal model over a thermal model. These early measurements have, however, been challenged. (Brown, McClymont and McLean 1974), and the resulting dispute (Mandel'stam, Beigman and Tindo 1975) has not clearly been resolved. The new observations of TCN (1984) are on a more solid observational footing and so should be able to provide a better diagnostic into the nature of the energetic electron population.

For isotropic electron distributions such as are expected on the basis of thermal models, the polarization of the emitted radiation should, of course, be zero. However, the presence of temperature gradients can lead to slight electron anisotropies and hence to low degrees of polarization (Emslie and Brown 1980). In addition, a small polarization can arise from the consideration of those photons which are backscattered by the photosphere (Tomblin 1972; Santangelo, Horstman and Horstman-Moretti 1973; Héroux 1975; Langer and Petrosian 1977; Bai and Ramaty 1978).

Early studies with non-thermal models, with (Langer and Petrosian 1977; Bai and Ramaty 1978) or without (Elwert 1968; Elwert and Haug 1971; Haug 1972; Bai and Ramaty 1978) photospheric albedo effects, were all based upon highly simplified angular distributions for the beam electrons. These early studies all ignored the effects arising from the geometry of the magnetic field, and most of them (except Brown 1972) also ignored the Coulomb scattering of the electrons within the target. Hence, early non-thermal studies tended to derive somewhat higher polarizations than did studies with thermal models. More recent studies (Leach and Petrosian 1981, 1983) have used a Fokker-Planck treatment to follow the evolution of an electron beam in the solar atmosphere and evaluate the characteristics of the bremsstrahlung hard X-rays produced

in such non-thermal models. This technique is a substantial improvement upon the previous theoretical analyses and permits us to assess more realistically the expected polarization in such models.

In §II we shall discuss the Fokker-Planck model results and compare them with the observations of TCN (1984). In §III we discuss why the predicted polarizations are substantially lower than those in earlier simpler models. Here also we discuss the influence of various parameters of the injected electron distribution and the target atmosphere which affect the polarization of the emergent bremsstrahlung radiation. Finally, we describe scenarios where high polarizations are still possible, with a view toward future observational efforts in this area.

II. POLARIZATION IN NON-THERMAL MODELS AND COMPARISON WITH OBSERVATIONS

In their Fokker-Planck studies, Leach and Petrosian (1981, 1983) assume the injection of a beam of non-thermal electrons at the top of a flare loop. They then investigate the evolution of this non-thermal electron population under the influence of the Coulomb collisions it suffers with ambient plasma particles. The essential three parameters used by Leach and Petrosian in their analyses are the reciprocal magnetic field scale length κ ($= d \ln B / ds$, where B is the strength of the guiding magnetic field and s distance from the top of the loop), and δ and α_0 , which describe the energy (E) and pitch angle (α) distribution of the injected electrons, viz $f(E, \alpha) \propto E^{-\delta} \exp(-\alpha^2/\alpha_0^2)$. One of the effects which would normally reduce the polarization of the X-rays and which has not been included in previous theoretical studies is the spatial curvature of the flare magnetic field. Since the orientations of the polarization vectors from different parts of a curved loop will differ, observations which do not resolve the loop will

measure a degree of polarization which is lower than that derived from smaller (and straighter) portions of the loop. Here, following Leach and Petrosian, we shall use flare loops which are semi-circular. Clearly, more complicated loop geometries could give rise to an even greater reduction in the degree of polarization.

For one of the flares observed by TCN (designated by these authors as flare 2I), we have information about the hard X-ray spectrum (S.R. Kane, private communication). These data allow us to fix the value for δ , thus leaving us with only two free parameters. We therefore in Figure 1 compare the observed degree of polarization for this flare with the calculated polarization curves for three models having different values of α_0^2 and κ . We note at this point, however, that there are two further effects to be considered which would reduce the degree of polarization measured from that predicted by the model;

(i) At these low X-ray energies there may be a significant contribution from a relatively unpolarized thermal background (Emslie and Vlahos 1980). A clear indication of such contamination would be an increase in the polarization with increasing X-ray energy. There may be some evidence of this in the data (TCN 1984).

(ii) Any variation in the flare characteristics over the relatively long (2 minutes) integration times of the observations will give rise to a lower observed polarization than would be expected from a typical isolated elementary burst of duration 10 seconds, especially if different elementary bursts are due to the energization of different loops (de Jager and de Jonge 1978; Emslie 1983; Kiplinger et al. 1983).

In addition, there are substantial error bars on the observations and some uncertainty inherent in the calibration procedure followed (TCN 1984). Consequently, we cannot set strict limits on the values of the model

parameters. However, the main point here is that, as we clearly show in Figure 1, a low degree of polarization does not necessarily militate against non-thermal models.

III. DISCUSSION AND SUMMARY

The reasons that the polarization estimates of Leach and Petrosian (1983) are lower than the earlier modeling estimates are as follows. As seen in a full Fokker-Planck analysis of the beam dynamics, any injected electron beam becomes increasingly isotropized as it penetrates further down through the solar atmosphere (Leach and Petrosian 1981). The rate at which the electrons diffuse in pitch angle is comparable to the rate at which they lose energy (Emslie 1978), and the bremsstrahlung cross-section is a decreasing function of electron energy (e.g. Koch and Motz 1959). Consequently, the bulk of the observed hard X-rays are emitted only after the electron beam has undergone much of this isotropization. Thus the integrated X-ray emission from the whole source will have the character of the emission from a highly broadened electron beam, independent of the original degree of electron beaming at injection. A spatially unresolved measurement of the hard X-ray polarization must then give rise to a low value. Certainly, the stronger the initial beaming of the electrons is, the higher will be the X-ray polarization, though we stress that this is no more than a weak effect once the Coulomb collisions have been properly incorporated into the analysis. Calculations for a variety of flare model parameters (Leach and Petrosian 1983) show that X-ray polarizations of around 25% are the most that can be expected, even from a highly beamed (low α_0^2) model with a uniform magnetic field. The effect of any non-uniformity in the magnetic field ($\kappa \neq 0$) is to further reduce the degree of polarization for the highly beamed models.

We now consider the influence of the parameter δ (the spectral index of

the injected electron beam) upon the hard X-ray polarization. (This parameter was fixed in our above comparison with flare 2I of TCN 1984 by independent observations.) The two cross sections for linearly polarized bremsstrahlung production are functions of the photon to electron energy ratio (k/E). These functional dependences are such that photons with larger k/E ("hard" photons) are, in general, more highly polarized than those with smaller k/E ("soft" photons) (Tseng and Pratt 1973). Injected electrons with a flat energy spectrum (i.e. small δ) will give rise to X-rays in which a greater proportion of the photons have low values of k/E (i.e. are "soft") and, therefore, the X-rays will be less polarized. Conversely, electron distributions which are steep (large δ) generally produce photons with k/E near unity ("harder" photons) and, thereby, result in a more highly polarized emission (cf. e.g., Figure 3b of Langer and Petrosian 1977). As demonstrated in Table I, the spectral index δ has a very substantial influence upon the observed polarization, and is at least as significant as the degree of electron beaming at injection. This effect has received little attention in the literature to date.

In summary, the observations by TCN (1984) of low hard X-ray polarization in solar flares are, in fact, consistent with both thermal and non-thermal models of hard X-ray production. Our hope of using polarization data as a discriminant rests upon our being able to observe the coronal component of the emission in isolation, for then any strong beaming of the non-thermal electrons, not yet having been smoothed away by collisions in the thick target, should result in quite a high polarization signature (Leach and Petrosian 1983), easily in excess of that predicted by thermal models (Emslie and Brown 1980).

Spatially resolved polarization measurements are not yet possible.

However, by looking at flares occurring just past the edge of the solar limb (Kane et al. 1982), it should be possible to observe the emission from the upper part of the flare loop without that emission being contaminated by the less polarized component from the eclipsed lower parts. Unfortunately, by the same token, the emission from this upper part of the loop will generally be no more than a small fraction of the total flare emission, thus presenting problems with statistical noise unless the observed flare is very large. Currently available instruments, such as the one used by TCN (1984), should, however, be capable (Lemen et al. 1982) of observing the coronal signal from the large flares which can be expected to occur during the next solar maximum.

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FIGURE CAPTION

Figure 1. A comparison between the polarization measured for flare 2I of Tramiel, Chanan and Novick (1984) and the polarizations calculated for three of the models of Leach and Petrosian (1983). The solid line is for a model with $\alpha_0^2 = 0.4$ and $\kappa = 0.0$, the dashed line is for a model with $\alpha_0^2 = 0.4$ and $\kappa = 1.5 \times 10^{-9}$, and the dotted line is for a model with $\alpha_0^2 = 0.1$ and $\kappa = 1.5 \times 10^{-9}$. ($\kappa = 1.5 \times 10^{-9}$ corresponds to a twentyfold increase in the magnetic field strength from the top of the flare coronal loop to the transition region, a distance of 2×10^9 cm.) All three models have a coronal density of $5 \times 10^9 \text{ cm}^{-3}$. For a flare at disk center the viewing angle would be 0° , for one on the solar limb it would be 90° .

